Spatio-temporal patterns in land use and management affecting surface runoff response of agricultural catchments—A review

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A B S T R A C T

Surface runoff and associated erosion processes adversely affect soil and surface water quality. There is increasing evidence that a sound understanding of spatial-temporal dynamics of land use and management are crucial to understanding surface runoff processes and underpinning mitigation strategies. In this review, we synthesise the effects of (1) temporal patterns of land management of individual fields, and (2) spatio-temporal interaction of several fields within catchments by applying semivariance analysis, which allows the extent and range of the different patterns to be compared. Consistent effects of management on the temporal dynamics of surface runoff of individual fields can be identified, some of which have been incorporated into small-scale hydrological models. In contrast, the effects of patchiness, the spatial organisation of patches with different soil hydrological properties, and the effects of linear landscape structures are less well understood and are rarely incorporated in models. The main challenge for quantifying these effects arises from temporal changes within individual patches, where the largest contrasts usually occur in mid-summer and cause a seasonally varying effect of patchiness on the overall catchment response. Some studies indicate that increasing agricultural patchiness, due to decreasing field sizes, reduces the catchment-scale response to rainfall, especially in cases of Hortonian runoff. Linear structures associated with patchiness of fields (e.g. field borders, ditches, and ephemeral gullies) may either increase or decrease the hydraulic connectivity within a catchment. The largest gap in research relates to the effects and temporal variation of patch interaction, the influence of the spatial organisation of patches and the interaction with linear structures. In view of the substantial changes in the structure of agricultural landscapes occurring throughout the world, it is necessary to improve our knowledge of the influence of patchiness and connectivity, and to implement this knowledge in new modelling tools.

Contents

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1. Introduction

Surface runoff and sediment generation have been recognised as major on-site soil degradation processes, since they adversely affect soil quality by reducing soil infiltration rates, water-holding capacities, nutrient content, organic matter and soil depth (Pimentel et al., 1995). As such, they contribute to the reduction of soil productivity and cause substantial environmental damage by depleting the soil resource (Lal, 1998). Surface runoff and sediment transport may also result in the export of sediment, along with biochemical and chemical components attached to fine sediment fraction. The associated off-site impacts may lead to reservoir siltation (Verstraeten and Poesen, 2000), reduction in the quality of surface waters (Wauchope, 1978; Sharpley et al., 1994) and increased risk of flooding and muddy floods (Boardman et al., 2003). A detailed understanding of the generation and pathways of both surface runoff and sediment from agricultural catchments to aquatic environments is therefore crucial.

A large number of studies have addressed the effects of land management on soil hydraulic properties and their relation to surface runoff generation under a wide range of agro-environmental conditions (Green et al., 2003; Ahuja et al., 2006; Strudley et al., 2008). Climate, soils, crop type and agronomic boundary conditions set the stage for farming operations and result in a site-specific seasonal pattern of soil hydraulic properties. This seasonality largely depends on the management system, the temporal fluctuations generally increasing with soil disturbance from no-till systems (NT) to conventional ploughing (CT). While the pattern is similar for most crops within one system, it is shifted between crops along the time axis (Fig. 1), creating a complex co-existence of states, e.g. of soil cover or roughness, at the same time within a catchment. This time shift is inherent in agricultural systems and allows the farmer to optimise labour and equipment capacities. The *first objective* of this paper is to synthesise the advances made in quantifying and modelling the effects upon infiltration and runoff processes of temporal patterns in land management within single fields or land use patches. In particular, we will focus on the temporarily variable impact of land management on soil bulk density, surface sealing, surface roughness and detention storage.

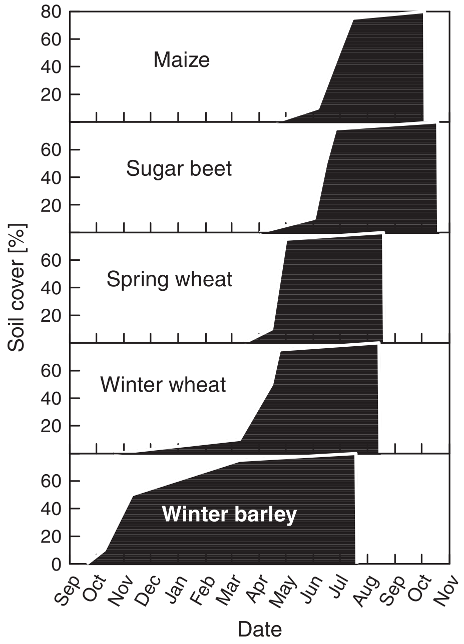

Fig. 1. Typical development of soil cover by different crops under Mid-European conditions; it also indicates indirectly the timing of main tillage operations occurring between harvest and planting of the respective crops; data taken from Schwertmann et al. (1987).

When moving from single fields to larger spatial scales it is important to consider that catchments are not farmed uniformly but are covered with different crops, and may exhibit complex land use patterns. Hence, the temporal pattern of hydraulic properties of single (field) patches also translates into a dynamic spatial pattern at the scale of a catchment. Different patches may interact, depending on the connectivity within the catchment (Lexartza-Artza and Wainwright, 2009), and this controls the passage of water from one part of the landscape (e.g. a single field) to another, as well as the overall runoff response at the catchment outlet (Bracken and Croke, 2007). The patchiness of an agricultural landscape, i.e. the number of patches with different hydrological behaviour, can have important implications for surface runoff generation. In addition, the spatial organisation of patches with different hydraulic behaviour and any linear structures associated with these patches, e.g. small ditches or small grass filters along field borders, will affect the passage of water through an agricultural catchment.

The effects of patchiness, spatial organisation of patches and linear structures on surface runoff response are most clearly seen in small headwater catchments. We limit our review to catchments with a surface area less than 10 km^2, in order to exclude the effects of channelized hydraulic systems. At this scale, channel networks arguably are less important, as the time constant of the network (i.e. travel time through it) is smaller than the infiltration phase (Beven and Kirkby, 1979). Nevertheless, the effects of patchiness within such small headwater catchments with first- and second-order streams (which typically contribute two-thirds of total surface water drainage networks; Leopold et al., 1964) may also have large-scale consequences (Freeman et al., 2007). The *second objective* of this review is therefore to synthesise the effects of the interaction between field and land-use patches on surface runoff response of agricultural catchments with a specific focus on patchiness.

2. Materials and methods

In this review we compare the effects of a wide variety of cropping and management operations upon surface runoff response. A direct comparison of results from different studies is difficult because the time at which cropping and management operations take place varies considerably across the world. In order to avoid absolute dates and to quantify the degree of variation in time caused by a certain management regime within an individual field we quantify the extent of temporal variation and the length of temporal autocorrelation by semivariograms (Rouhani and Myers, 1990; Kyriakidis and Journel, 1999), which will be calculated from measured data taken from literature. Analogously to the temporal description of data, we will also use semivariograms to quantify the degree of variation in space resulting from landscape patchiness, assuming virtual agricultural landscapes determined by a varying number of fields per area (2 to 64 fields per km^2 corresponding to field sizes of 50 to 1.56 ha; Fig. 2). For simplicity, square-shaped fields were assumed except for the largest class, which has the same width as the second largest class but twice the length and thus allows the effect of differing length/width ratios to be judged.

In general, these semivariograms express the variance in data with increasing lag in time (or space). They allow three major characteristics of temporal (or spatial) data to be determined: (i) the short-term (or short-distance) variability of a property and the accuracy of applied measuring technique is represented in the nugget effect (N) of the semivariogram indicated at a time (or space) lag of zero; (ii) the maximum variability of a property in time (or space) is given by the sill (S); and (iii) the time (or space) lag at which two states of a property become independent from each other is denoted as range (R). The extent of seasonality (or spatial variability) is hence given by the partial sill (sill minus nugget) and the temporal (or spatial) range. A short additional description of the concept and terminology of

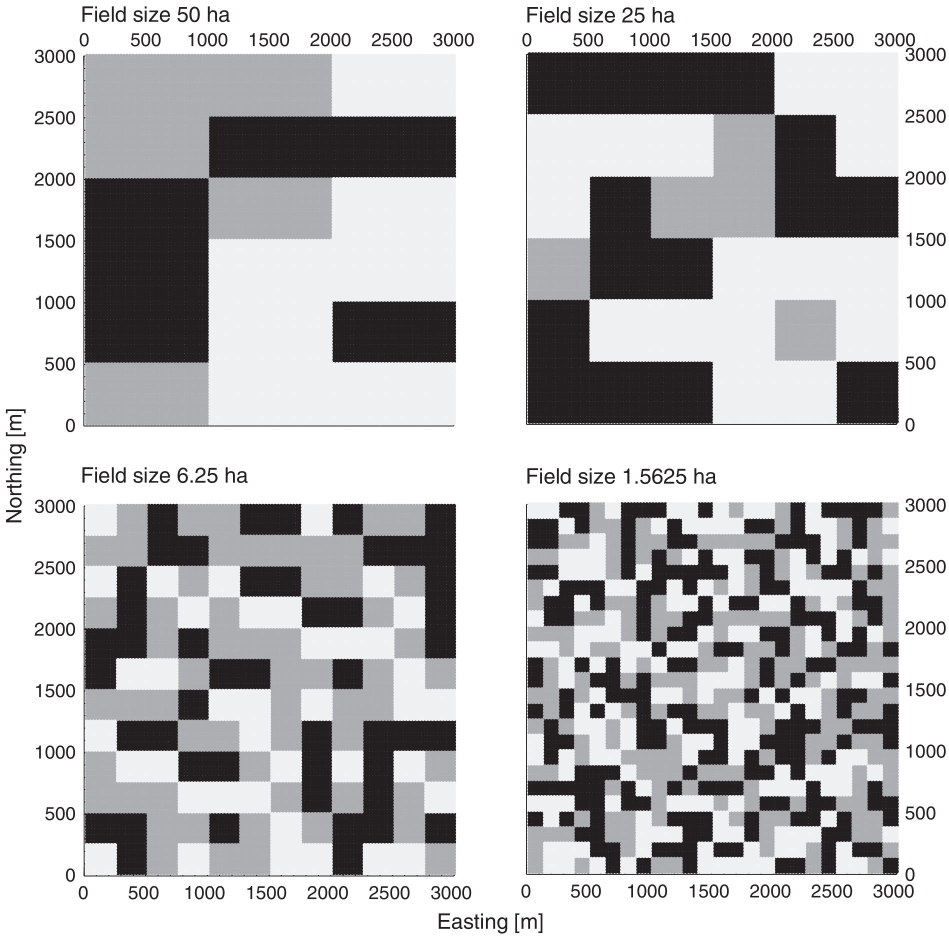

Fig. 2. Patchiness in a virtual 9 × 9 km² landscape segment with a 3-year crop rotation and different field sizes (1.56–50 ha); distribution of the position of each field within the crop rotation was determined using a random generator (GraphPad Software Inc., USA).

semivariances and the interpretation of semivariance models is given in Appendix A.

It is important to note that second-order stationarity assumed for semivariograms (Rossi et al., 1992) will not always be sufficiently met on smaller timescales, as sudden breaks occur that exceed the general behaviour, e.g. soil cover may change by almost 100% from one day to the next if ploughing is applied, while the semivariogram indicates a mean change in soil cover of only 3.6% for a lag of one day within a rotation. The semivariogram at short time lags thus underrates the true variation at such breaks and overrates it in-between, but still allows us to generalise a rotation sufficiently well and to make comparisons between different land-use systems. The same restriction operates when semivariograms are applied to spatial data. The semivariogram at short spatial lags underrates the true variation at field borders and overrates it within fields, but it also should still allow us to generalise catchments and to make comparisons between different degrees of patchiness.

All semivariograms were determined using the GNU R version 2.6 (R Development Core Team, 2007) and the supplementary geostatistical package gstat (Pebesma, 2004).

3. Within-field seasonal patterns in surface runoff generation potential

3.1. Soil bulk density

The land management operations on which intensive agriculture depends result in the creation of tramlines or wheelings. These wheel tracks have reduced infiltration capacity, creating a small-scale variability in infiltrability; they restrict subsurface flow and increase return flow and they redirect surface runoff (Tullberg et al., 2001, Green et al., 2003, Silburn and Hunter, 2009). Tillage is intended to remove these adverse effects of wheeling and provide other positive effects, such as incorporation of residues and seeds. It disturbs the soil and thus influences soil hydraulic properties. The most intensively investigated soil properties in this context are soil bulk density and soil porosity. In general, tillage decreases bulk density of the tilled soil layer and subsequently soil reverts back to approximately its original density (e.g. Onstad et al., 1984; Franzluebbers et al., 1995; Ahuja et al., 2006). The temporal changes of bulk density are more pronounced in the case of CT than NT, although NT may cause a long-term increase in macroporosity due to increased faunal activity, which in some cases may even cause a larger total porosity under NT than under CT (e.g. Benjamin, 1993; Katsvairo et al., 2002). The seasonality of bulk density is low for NT and pronounced for CT. In the example shown in Fig. 3, NT exhibits a pure nugget effect, indicating that bulk density varies randomly during the year by about 0.045 Mg m^{-3}, while CT produces a clear seasonal pattern yielding a periodic semivariogram (0.055 Mg m^{-3} partial sill), in addition to the same random variation (nugget) as found for NT. The pattern ranges over one year, reflecting the rotation consisting of annual crops.

Despite the difficulties of fully representing the interactions between tillage operations, soil properties and environmental conditions during tillage (Alberts et al., 1995), there are empirical modelling approaches in use to relate bulk density to tillage operations with different tillage implements (Williams et al., 1984; Chen et al., 1998). The approach of Williams et al. (1984) was originally developed for the

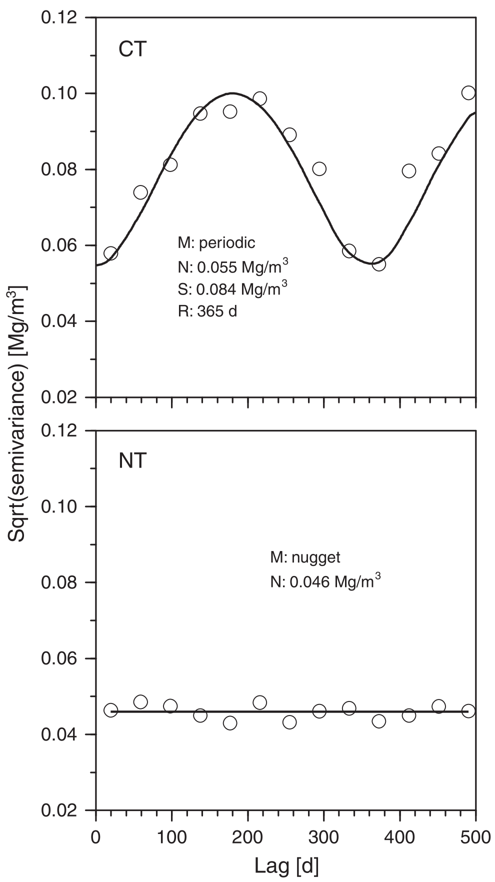

Fig. 3. Semivariogram of seasonal variation of bulk density in 0–50 cm depth for conventional tillage CT (mean density: 1.19 Mg/m³) and no-tillage NT (mean density: 1.27 Mg/m³); planted crops are sorghum (*Sorghum bicolor* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.); bulk density was measured 57 times during a 2-year period from July 1991 to June 1993 (Franzluebbers et al., 1995); the square root of the semivariance is displayed to yield the unit of bulk density; M, N, S and R are model type, nugget, sill and range of the theoretical semivariograms.

EPIC model and is similarly implemented in the WEPP (Alberts et al., 1995) and RZWQM (Hanson et al., 1998) models.

$$\rho_t = \rho_{t-1} - \left[\left(\rho_{t-1} - \frac{2}{3}\rho_c\right) T_{ds}\right] \tag{1}$$

where ρ_t is the bulk density after tillage [kg m^{-3}; for all ρ], ρ_{t-1} is bulk density before tillage, ρ_c is the consolidated soil bulk density at 0.033 MPa of tension, and T_{ds} is the fraction of the soil surface disturbed by the tillage implement. This fraction depends on both the implement used and the crop residue type (Alberts et al., 1995). Consolidated soil bulk density ρ_c represents the bulk density without any tillage effect, which depends on texture, soil organic matter and cation exchange capacity of clay.

Continuous simulation must also model reconsolidation, which happens after tillage and is mainly associated with subsequent rainfall events (Mapa et al., 1986). Most studies report that a maximum bulk density in the topmost soil layer (<0.1 m soil depth) is reached after approximately 100 mm of rainfall (Onstad et al., 1984; Fohrer et al., 1999; Schiettecatte et al., 2005; Knapen et al., 2008), which seems to underrate the range in Fig. 3. For deeper layers (>0.1 m soil depth), only a slight reconsolidation due to rainfall (Rousseva et al., 1998) or even no effects were found (Karunatilake and Van Es, 2002). For the uppermost soil layer one of the most frequently used equations, originally developed by Onstad et al. (1984), is implemented in the EPIC (Williams et al., 1984), WEPP (Alberts et al., 1995) and RZWQM (Hanson et al., 1998) models:

$$\rho_d = \rho_t + \Delta\rho_{mx} \frac{R_c}{0.01 + R_c} \tag{2}$$

where ρ_d is the bulk density after rainfall, ρ_t is the bulk density after tillage, and $\Delta\rho_{mx}$ is the maximum increase in soil bulk density with rainfall, which can be estimated from ρ_t and the soil clay content (Alberts et al., 1995), and R_c is the cumulative rainfall since tillage [m].

Such empirical approaches are typically only implemented in erosion models, which are mostly applied in fields or catchments of up to several square kilometres, while soil disturbance by tillage is not usually taken into account in hydrological modelling at larger scales. Technically it would be possible to implement such approaches in larger-scale models either by directly determining the effects of tillage on soil-water retention characteristics (Diiwu et al., 1998; Van Es et al., 1999; Ndiaye et al., 2007) or by combining bulk density algorithms like Eqs. (1) and (2) with pedotransfer functions developed to predict water retention characteristics, using soil texture, soil organic matter content and bulk density (e.g. Gupta and Larson, 1979; Scheinost et al., 1997; Wösten et al., 2001; Rawls et al., 2003). However, such an implementation on larger scales is hampered by poor availability of data relating tillage operations on different fields.

3.2. Soil sealing

Infiltration into agricultural soils is often governed by the development of a thin seal or crust of low permeability (Duley, 1939) resulting from raindrop impact on uncovered soil surfaces, as evaluated in many studies. In general, sealing (synonymous here with the term crusting) decreases infiltration rates rapidly and pronouncedly, often by more than one order of magnitude (Horton, 1939) and hence increases runoff coefficients.

Seal development is on the one hand governed by a number of site-specific, more or less time-invariant parameters, such as soil texture, soil organic carbon, slope steepness etc. (Bradford and Huang, 1992), and on the other hand depends on the seasonality of (i) rainfall, (ii) soil surface conditions due to tillage and (iii) soil cover by living and dead biomass. Moreover, crusts are removed by tillage and by natural processes like drying or wetting or biological activity. Site-specific seasonality in both rain energy, which causes sealing (Mualem et al., 1990), and rainfall amount, which leads to runoff, must also be considered. Although connected, both rain properties differ in their seasonal distribution, which becomes obvious when comparing the seasonal distribution of rainfall and the seasonal distribution of rain erosivity, which mainly depends on rain energy (Fig. 4A). In general, rain erosivity or kinetic energy is less evenly distributed than rainfall, which should lead to a corresponding seasonality in the sealing initiation. Seasonality in rain erosivity (Fig. 4B) may differ to a larger extent between different areas than field conditions. Because of the discrepancy between the seasonality of rainfall and rain kinetic energy, similar amounts of rain can cause different amounts runoff, depending on the time of the year, even without taking into account the seasonality of the soil surface conditions due to agricultural operations. The strongest variation in sealing potential due to agricultural operations results from varying soil cover. Cover under CT has a more pronounced seasonality than mulch tillage, organic farming (Fig. 5) or NT, where soils are kept more evenly covered either by living or dead biomass. Compared to soil cover, the variation of other soil properties affecting potential seal development, such as aggregate stability, is less pronounced (Fig. 6), and their effect on seal development is less clear.

The change of infiltration rate due to sealing is most often modelled by negative exponential equations (Horton, 1939; Morin and Benyamini, 1977; Assouline and Mualem, 1997; Schröder and

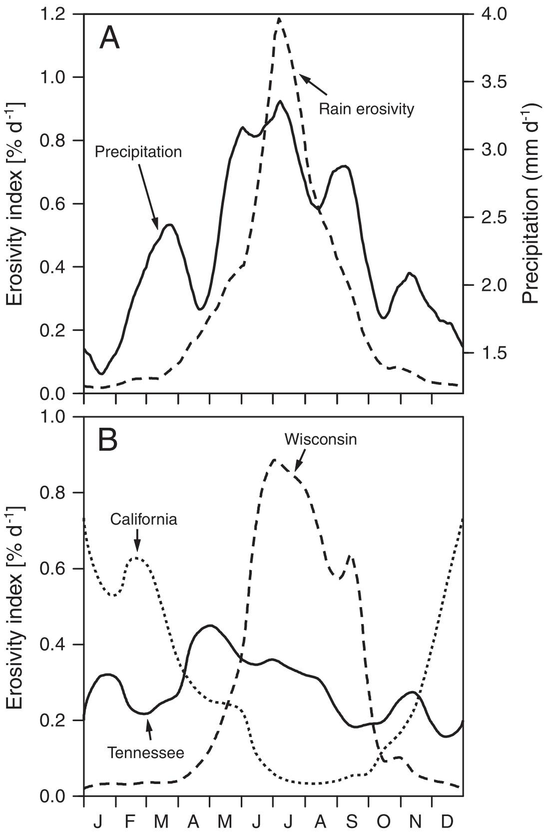

Fig. 4. (A) Comparison of seasonal variation of precipitation and erosivity index for a location in Germany (data taken from Fiener and Auerswald, 2006); (B) Comparison of the seasonal erosivity index distributions for three locations in the United States (San Luis Obispo in California, Memphis in Tennessee and Madison in Wisconsin); data taken from Wischmeier and Smith (1978); erosivity index = erosivity per day/erosivity per year (EI would be 0.27% d^{-1} in the case of equal distribution).

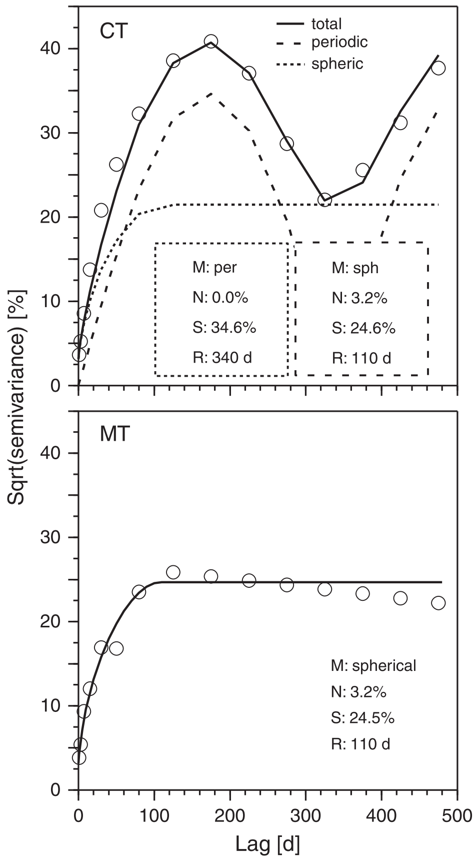

Fig. 5. Semivariogram of the seasonal variation of soil cover for rotations with two tillage systems (conventional farming CT, mean cover = 26%; mulch tillage MT, mean cover = 49%); data taken from Auerswald et al. (2000); the lower cover of conventional farming is caused by the pronounced seasonality, where crops provide similar cover as in the mulch tillage cases, but low cover characterises the periods between two crops. This leads to an almost identical short-range (100 d) variation of 24% caused by common operations in both systems, but CT additionally has a pronounced periodic variation (35%) caused by tillage. Both variations in the case of CT are given, together with a nested semivariogram (= total); for details see Appendix A; the square root of the semivariance is displayed to yield the unit of soil cover; M, N, S and R are model type, nugget, sill and range of the theoretical semivariograms.

Auerswald, 2000) depending on rain amount or rain energy, more or less empirical parameters representing soil properties and soil cover. General versions of the most commonly used equations are given in Eqs. (3) and (4):

$$K_{cr} = K_f + \left(K_0 - K_f\right) \cdot e^{-C \cdot Ekin_{eff}} \quad (3)$$

where K_{cr}, K_f, and K_0 are the hydraulic conductivity of the sealed/crusted soil, the final hydraulic conductivity of K_{cr}, and the hydraulic conductivity of an unsealed soil (beginning of an event), C is a decay constant influenced by soil properties determined either individually, for example from rainfall experiments, or derived from empirical relations to soil properties, and $Ekin_{eff}$ is the effective rainfall energy at the soil surface.

$$Ekin_{eff} = Ekin \cdot (1 - Cover) \quad (4)$$

where $Ekin$ is the kinetic rainfall energy and $Cover$ gives the relative soil cover by plants and plant residues. Some authors include surface roughness either in Eq. (3) (e.g. Risse et al., 1995) or take roughness into account when calculating $Ekin_{eff}$ in Eq. (4) (e.g. Linden, 1979).

While these kinds of models have been successfully applied to describe rainfall experiments, their application for continuous modelling is limited by the difficulty in predicting K_f, K_0 and C and the crust recovery due to soil cracks, earthworm activity and plant–soil interactions etc., which are again variable in respect of climate and season. Potentially applicable approaches to quantifying such recov-

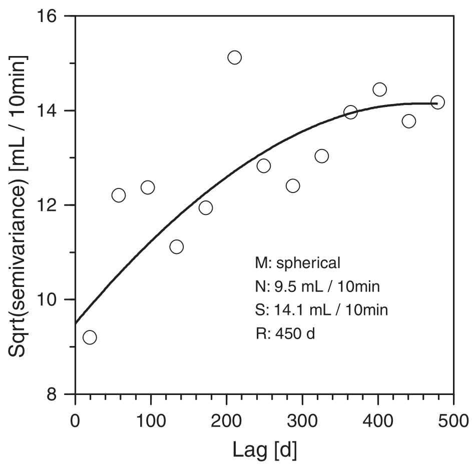

Fig. 6. Semivariogram of seasonal variation of aggregate stability (expressed as percolation stability) for mulch tillage taken from Fiener and Auerswald (2007). Aggregate stability varies rather rapidly, e.g. due to tillage operations. This leads to a large nugget effect (square root of about 9), while the square root of the partial sill is only about 5 ml/10 min (for a mean percolation stability of 31 ml/10 min); the square root of the semivariance is displayed to yield the unit of percolation stability; M, N, S and R are model type, nugget, sill and range of the theoretical semivariograms.

ery effects include a model to determine the pattern of cracks in crusted soils due to shrinkage processes (Valette et al., 2008), or the work by Bronswijk (1989, 1998) on subsidence and shrinking of soils. Introducing sealing in catchment-scale models is additionally hindered by the large spatial heterogeneity of seal development resulting from small-scale differences in soil properties, soil cover (e.g. Ruan et al., 2001), microtopography, management, etc. Nevertheless, some applications of hydrological or erosion models have successfully integrated sealing processes as one of the key drivers of surface runoff (e.g. Cerdan et al., 2002; Fiener et al., 2008).

3.3. Surface roughness and detention storage

Surface roughness in agricultural fields may result either from tillage operations or from residues at the surface (Gilley et al., 1991) and subsequently decays again, causing a clear seasonality depending on the cropping and management system used. Tillage creates both an oriented roughness due to the direction of tillage, and a random roughness (Govers et al., 2000). This differentiation is important insofar as oriented roughness in general is more pronounced than random roughness (compare Figs. 7 and 8). Semivariance of oriented roughness perpendicular to tillage direction rises to about 10 cm (Fig. 7), while it is only about 0.2 cm for random roughness, if the unit of Fig. 8 is converted to cm using the regression by Jester and Klik (2005). However, the effects of oriented roughness depend on its orientation relative to the main slope (Foster et al., 1997), with the largest effect on runoff reduction and detention storage being seen when roughness is oriented perpendicular to the main slope and the least effect evident when it is in the direction of the slope (where only random roughness is relevant). In contrast, random roughness is much smaller but acts independently of the slope aspect. Roughness decay is governed by three factors: the stability of the soil, which depends on cohesive substances, namely clay (Kemper and Rosenau, 1984), organic matter (Tisdall and Oades, 1982), soil moisture (Cousen and Farres, 1984; Kemper and Rosenau, 1984; Auerswald et al., 1994), roots and mycelia (Oades, 1987; Marinissen and Dexter, 1990; Thomas et al., 1993); the extent of forces that interact with the surface, which mainly result from rain (Zobeck and Onstad, 1987) and wind (Saleh and Fryrear, 1999); and the degree to which the surface roughness is protected from these forces, which mainly results from soil cover. Tillage thus creates roughness, but by destroying the soil cover (Colvin et al., 1981) and weakening the aggregates (Auerswald, 1993) also promotes its subsequent decay.

Roughness in turn affects (i) runoff direction due to oriented roughness (Govers et al., 2000), (ii) seal development, (iii) runoff velocities (Fig. 9) and (iv) detention storage. Modelling assumes that seal development is retarded when tillage operations create a random roughness larger than 40 mm (Rawls et al., 1990) but otherwise tillage removes residues that protect soils from raindrop impact, and thus indirectly increases the potential for subsequent seal development.

The effect of surface roughness on runoff velocity is mostly integrated in hydrological modelling by relating surface roughness and residue cover to hydraulic roughness coefficients in one of the common kinematic wave equations (e.g. Weisbach, Chezy and

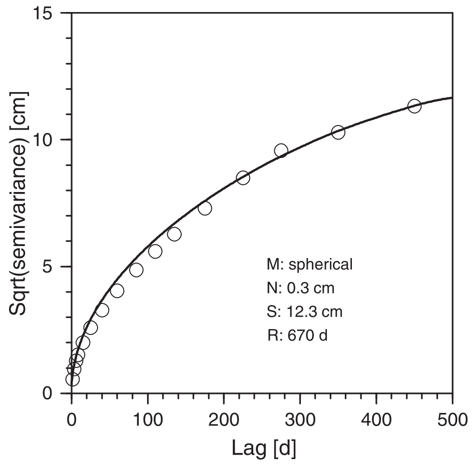

Fig. 7. Semivariogram of seasonal variation of oriented roughness perpendicular to tillage direction; data of oriented roughness of different soil management from Takken et al. (2001b) combined with management data representing a potato (*Solanum tuberosum* L.), winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and winter wheat rotation (Fiener et al., 2008); because of the potato in particular the oriented roughness varied substantially, with a square root of the partial sill of 12.0 cm for a mean orientated roughness of 8.0 cm; the square root of the semivariance is displayed to yield the unit of oriented roughness; M, N, S and R are model type, nugget, sill and range of the theoretical semivariograms.

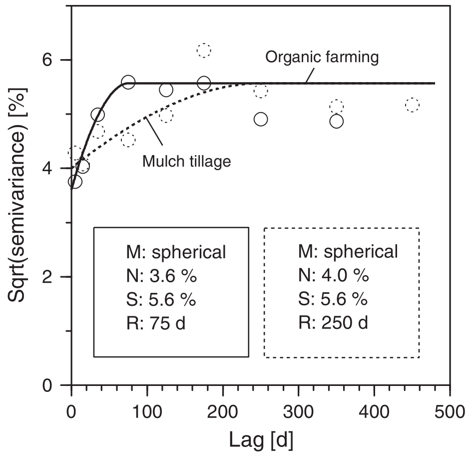

Fig. 8. Semivariogram of random roughness measure *RFR* used in the runoff and erosion model EUROSEM (Morgan et al., 1998); *RFR* calculated from a 3-year data set of fields under organic farming (continuous line and symbols) and mulch tillage (dashed line and symbols), both with a potato, winter wheat, maize and winter wheat rotation (Kaemmerer, 2000); the square root of the semivariance is displayed to yield the unit of *RFR*; M, N, S and R are model type, nugget, sill and range of the theoretical semivariograms.

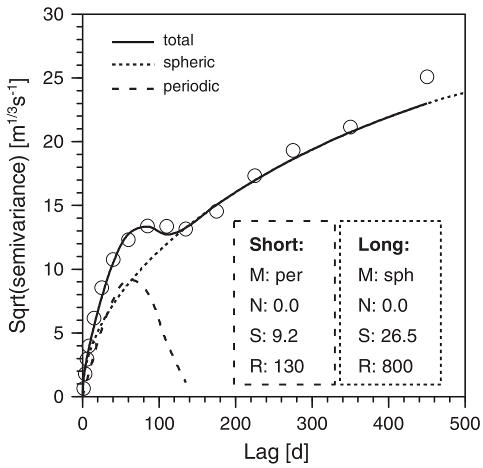

Fig. 9. The semivariogram of the seasonal (periodic) variation in residue induced hydraulic roughness (mean Strickler coefficient $K=39$) shows a pronounced variation in runoff velocity within a crop (lag<130 d) and an even stronger variation between crops (lag>200 d) leading to a nested semivariogram. The superimposed long-term semivariogram (spheric) would be expected to transform into another periodic semivariogram of the rotation length if the experimental period covered several rotation cycles. Residue cover data from a potato, winter wheat and maize cropping sequence applying mulch tillage were taken from Fiener et al. (2008) to calculate roughness according to Gilley et al. (1991); Strickler's *K* (Dyck and Peschke, 1995), which is the inverse of Manning's *n*, was used; it is superior to *n* in this analysis because it relates linearly to runoff velocity; the square root of the semivariance is displayed to yield values directly comparable to *K*; M, N, S and R are model type, nugget, sill and range of the theoretical semivariograms.

Manning equations). Data needed to calculate hydraulic roughness from empirical relationships (e.g. Roels, 1984; Gilley et al., 1991; Gilley and Finkner, 1991) are either measured (e.g. Fig. 9) or modelled via residue decay approaches, empirical relationships between tillage implements and roughness (Alberts et al., 1995), or random roughness decay as a function of the amount of rainfall or rainfall kinetic energy (e.g. Burwell and Larson, 1969; Johnson et al., 1979; Magunda et al., 1997).

Detention storage is the portion of the rain that remains on the ground surface during rainfall and is absorbed by infiltration after a rainfall event ends (Horton, 1933). The extent of detention storage can be approximated based on slope and surface roughness due to tillage (Onstad, 1984; Huang and Bradford, 1990; Mwendera and Feyen, 1992). Detention storage can exceed 20 mm for a freshly mouldboard ploughed soil surface with zero slope (Moore and Larson, 1979) but in most cases it is one order of magnitude lower (Govers et al., 2000). The effects of a residue cover on detention storage are more difficult to determine, as they depend on the type and location of residues (within tillage furrows or on ridges). Moreover, the location of these residues can change during runoff events.

The effects of an anisotropy in tillage roughness on runoff direction and hence duration (e.g. Souchère et al., 1998) was also integrated into models focusing on surface runoff and erosion on hillslopes or in small catchments (Takken et al., 2001a,b,c), which allowed the patterns of rill and ephemeral gully erosion to be predicted much more accurately than by using topography alone.

4. Catchment-scale interaction between patches, patchiness and surface runoff response

When moving from the field to the catchment scale, surface runoff response becomes governed by areas differing in land use, referred to from now on as patches to include different fields but also other land use types. The interaction of these patches depends on their spatial organisation. The asynchronous temporal variation in their runoff generation potential and the temporal and spatial variation of rain events cause a complex behaviour, which does not allow scaling of results from homogenous plots directly to catchment scale. Moreover, linear structures play an important role in catchment runoff response. Such structures can either be associated with patch borders, e.g. ditches, fences, farm roads or grass filters, or result from (large) patch sizes in the case of rill and (ephemeral) gully development. Such linear structures that result from runoff itself may cut through linear structures separating different fields and connect them, or they may concentrate runoff and cause a fast by-pass of large parts of the catchment area (Fig. 10).

To address the effects of man-made patchiness in agricultural catchments on runoff response it is necessary to evaluate the effects of the number of patches per unit area, the spatial organisation of these patches, and the linear structures typically associated with (field) patches. We will not consider within-field variability, which has been treated in several other studies (Govindaraju et al., 2001, Olsson et al., 2002, Meng et al., 2006) because the contrasts within a field are usually much smaller than the contrasts between patches.

4.1. Effects of field size

Rain excess differs depending on rainfall characteristics and infiltration characteristics of the patches. While some fields or patches produce runoff, run-on infiltration can occur in others. Patches differing in hydraulic roughness and detention storage will affect runoff velocity, peak discharge and run-on infiltration, which in turn depend on runoff travel time. Run-on infiltration reduces runoff volume and peak discharge (e.g. Corradini et al., 1998; Assouline and Mualem, 2006). Furthermore, mulch cover (e.g. Greb et al., 1967; Steiner, 1994) and tillage direction (e.g. Takken et al., 2001b,c) can increase detention storage, slow down runoff and hence prolong runoff duration. However,

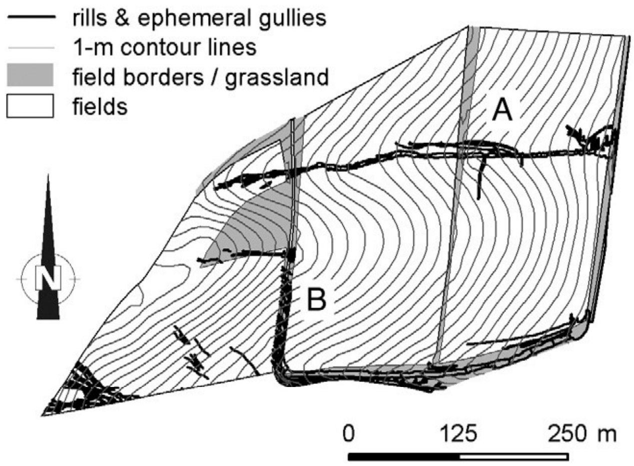

Fig. 10. Change in the connectivity between adjacent fields due to linear erosion. (A) An ephemeral gully up to 8 m wide and 0.5 m deep cut through field borders and caused a short cut between the fields and the ditch along the eastern field margin. (B) Many small rills cut through the field border between two adjacent fields and connect the sheet flows on both. Linear erosion was digitised from aerial photos (scale 1:10,000) taken 5 d after a 53 mm event. For details on catchment properties see Fiener and Auerswald (2003).

to our knowledge there are no studies evaluating the effects of field size (or field size dependent patchiness) on agricultural catchment runoff response. This is almost impossible to study in real-world experiments but modelling approaches like multifractal scaling, which has already been used successfully to study the effects of within-field variability of hydraulic conductivity and rain on runoff–run-on behaviour (Meng et al., 2006), could also be used in this case.

The effects of patchiness are more evident and easier to study in situations where the temporal variation is smaller than the spatial variation and thus causes a spatial pattern which is almost constant in time. Such situations can be found in heterogeneous natural vegetation like in semi-arid landscapes, where vegetated and bare patches co-exist. Many studies have shown that runoff generated on bare areas re-infiltrates in the vegetation patches and hence reduces catchment outflow (Sanchez and Puigdefabregas, 1994; Valentin et al., 1999; Dunkerley, 1999; Puigdefabregas, 2005). For example, in the studies by Ludwig et al. (1999, 2005), a loss of landscape patchiness led to an overall 25% loss of plant available soil water, and banded vegetation was more effective (plus 8%) in capturing run-on water compared to a stippled pattern. Bracken and Croke (2007) concluded that in these environments the loss of patchiness has the greatest influence on the ability of hillslopes to reduce surface runoff and hence to capture rainfall for biomass development.

In general, these results should also apply to agricultural catchments but the spatial heterogeneity in agricultural catchments is dependent upon their temporal variability, e.g. where all fields are cropped with the same rotation but differ in their position within the rotation. Under such conditions, research is mainly focused on the temporal variation within homogenous plots, which is a prerequisite to understanding the spatial variation, while the influence of patchiness itself is less proven for a consistently changing pattern of runoff and run-on patches which arises from the asynchronous seasonality of cropping in different fields. Experience from land reconsolidation projects shows that a reduction in patchiness resulting from increasing field sizes increases runoff volume and peak discharge (Luft et al., 1981; Bucher and Demuth, 1985), although the multitude of changes associated with land reconsolidation means some uncertainty remains regarding the contribution of different measures to the overall effect (Bronstert et al., 1995).

This restriction does not apply for changes in the opposite direction associated with strip cropping, where patchiness is increased for soil conservation purposes to reduce soil loss and runoff

(Smith et al., 1991; Natural Resources Conservation Service, 2004), proving the influence of patchiness. Nor would it apply for modelling studies, though there are none that explicitly focus on the effects of field size dependent patchiness. In most cases, land use and/or management change are simultaneously evaluated (e.g. Fohrer et al., 2001; Srivastava et al., 2002; Souchère et al., 2005; Bormann et al., 2008). Nevertheless, there is some indication that decreasing field sizes and hence increasing patchiness reduce surface runoff (Fohrer et al., 2005; Bormann et al., 2007), although the opposite can also be true. In an abandoned Mediterranean environment, small terraced patches produced more saturation runoff than large land patches, as a result of the combined effect of enhanced saturation in parts of the abandoned terraces and accelerated runoff in an old ditch system associated with the terraces (Gallart et al., 1994).

Using spatial semivariograms, the spatial autocorrelation length increases as expected with increasing field size for all tested parameters (Fig. 11). It is slightly larger than the field edge lengths because of some adjacent fields cropped identically (Table 1). The autocorrelation length was independent from season, which indicates that fields cultivated with different crops differ during all seasons, although the extent of variation (sill) varies.

The spatial variance of bulk density is least pronounced in January (close to the pure nugget) and most pronounced in August with the square root of the partial sill being 0.15 Mg/m^3. Analogously, the most pronounced variation in soil cover can be found in August (partial sill about 40 to 45%) when some crops are already harvested, while – in contrast to bulk density – in July the differences between fields are smallest, as all crops exhibit a large amount of biomass (partial sill about 13%). Compared to soil cover and bulk density, seasonal differences in spatial variance of oriented roughness are small. It is most pronounced in August (square root of partial sill about 1.4 cm) because of the large differences between already harvested fields (OR = 0 cm) and fields under sugar beet (OR = 3 cm). In general, the spatial variation of roughness is moderate in the presented crop rotation (averages in January and August are 1.3 and 1.1 cm, respectively) but could be much larger if potato (OR = 25 cm) were included in the rotation.

The maximum relative variance of all evaluated parameters (square root of partial sill relative to the average over all fields) increased from bulk density (12%) to soil cover (135%) and oriented roughness (140%). The hydraulic effect of oriented roughness, however, also depends on the relation of tillage direction to direction of slope, which was not considered in this evaluation. In general, the spatial variation of all hydrologically important parameters was most pronounced for partly harvested agricultural areas (August) and the effects of patchiness upon surface runoff response should be therefore most pronounced in the case of heavy summer storms.

Table 1
Theoretical semivariograms (spherical model) of the experimental semivariances for the months with the highest and the lowest spatial variability as shown in Fig. 11; semivariances are given as square roots to allow for a comparison with the original data.

Field size (ha)	Edge length (m)	Nugget	Partial sill	Range	Nugget	Partial sill	Range
		Bulk density					
		August			January		
		(Mg/m³)	(Mg/m³)	(m)	(Mg/m³)	(Mg/m³)	(m)
50	500/1000	0.00	0.15	839	0.01	0.02	1912
25	500	0.00	0.15	733	0.00	0.02	724
6.25	250	0.00	0.14	320	0.00	0.02	296
1.565	125	0.00	0.15	167	0.00	0.02	170
		Soil cover					
		August			July		
		(%)	(%)	(m)	(%)	(%)	(m)
50	500/1000	2.4	44.2	1341.	0.0	13.4	850
25	500	0.0	45.0	721	0.0	12.7	744
6.25	250	0.0	39.6	306	0.0	13.8	310
1.565	125	0.0	40.5	171	0.0	13.8	165
		Oriented roughness					
		August			January		
		(cm)	(cm)	(m)	(cm)	(cm)	(m)
50	500/1000	0.37	1.46	1510	0.25	0.98	1509
25	500	0.00	1.53	721	0.00	1.02	721
6.25	250	0.00	1.35	305	0.00	0.90	305
1.565	125	0.00	1.37	171	0.00	0.92	171

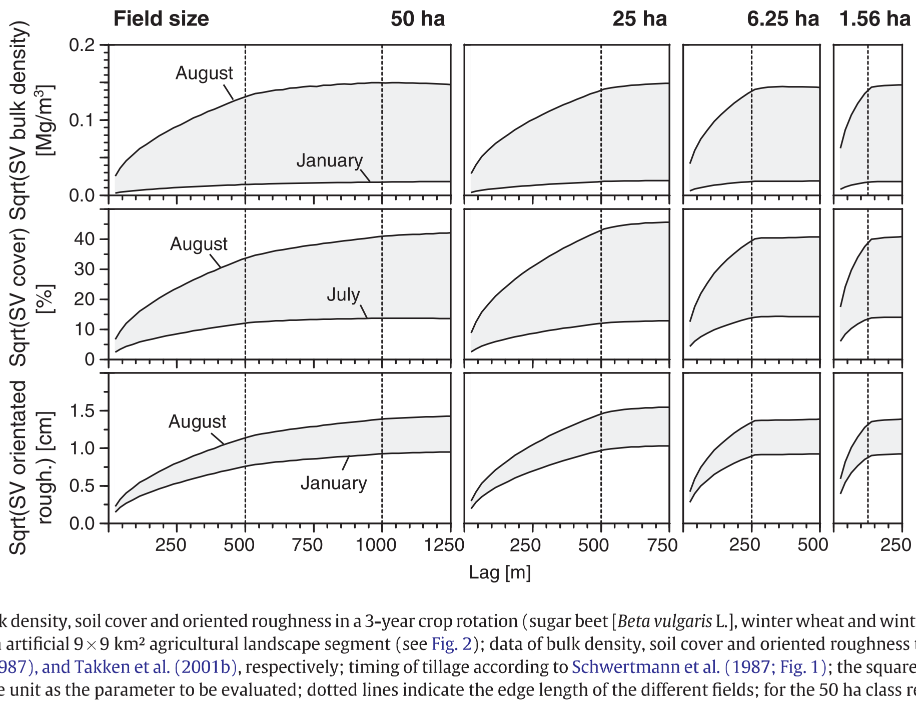

Fig. 11. Semivariograms of bulk density, soil cover and oriented roughness in a 3-year crop rotation (sugar beet [*Beta vulgaris* L.], winter wheat and winter barley [*Hordeum vulgare* L.]), depending on patchiness of an artificial 9 × 9 km² agricultural landscape segment (see Fig. 2); data of bulk density, soil cover and oriented roughness taken from Franzluebbers et al. (1995), Schwertmann et al. (1987), and Takken et al. (2001b), respectively; timing of tillage according to Schwertmann et al. (1987; Fig. 1); the square root of the semivariances (SV) are displayed to yield the same unit as the parameter to be evaluated; dotted lines indicate the edge length of the different fields; for the 50 ha class rectangular fields with a length/width ratio of 2 were assumed, which results in two dotted lines instead of one in the case of the squared fields (1.56, 6.25 and 25 ha, respectively); only the months with the largest and the lowest variance of the individual parameter are shown.

4.2. Effects of spatial organisation of land-use patches

Within the last few decades, increasing attention has been given to the effect of spatial organisation of land-use patches on hillslope or catchment surface runoff response. Most studies have been carried out under an engineering perspective, e.g. to evaluate the best location of buffer strips for soil and water conservation (e.g. Correll, 2005; Dabney et al., 2006), but also on the general runoff response following different arrangements of patches (or raster cells in models). For example, Western et al. (2001) have modelled the effect of grid cells high in soil moisture on saturated surface runoff of a small (10 ha) grassland catchment. The catchment produced surface runoff significantly earlier if these wet grid cells were connected along the drainage pathway than if randomly distributed. This effect levelled out in the case of larger (30–40 yr) rainstorms. Ziegler et al. (2007) quantified the effects of patchiness and optimised arrangement of patches of six land-use categories (abandoned field, young secondary vegetation, upland field, intermediate secondary vegetation, forest and grassland) to reduce surface runoff in two upland catchments in Vietnam. Independent from modelled event size, an increasing patchiness and an optimised patch arrangement, which maximises the number of transfers between patches of different hydrological behaviour, substantially reduced catchment outflow without changing the proportions of different land uses.

However, optimum patch arrangement can only be found in the case of permanent differences in hydrological behaviour of patches. In arable landscapes where fields are shifted annually in a rotation, such optimizations might only be possible if arable fields are combined with permanently buffering land uses, like forest or grass buffers.

4.3. Effects of linear structures

In agricultural catchments, relatively small linear structures, whether intentionally constructed or by-products of field management, are often associated with field borders. Some of these linear structures are more or less stable, while others vary in space and time. As these are often associated with microtopograhical elevations or depressions, they cause runoff concentration, and affect hydraulic connectivity and the surface runoff response of catchments (e.g. Van Oost et al., 2000; Van Dijk et al., 2005).

Common stable linear structures in agricultural areas associated with patchiness are (i) field margins, (ii) field roads, often interrupting flow pathways and concentrating runoff, (iii) ditches along field borders, used to drain agricultural land, and (iv) any kind of vegetated filters at field borders, either perpendicular to flow direction, e.g. grass filter strips at the downslope end of fields, or along the drainage pathway, e.g. grassed waterways. An intermediate between linear and spatial structures are tile drains, which will also be considered here. Even if these structures are more or less stable in space, their hydrological behaviour may change in time. For example, ditches in a 0.91 km^2 agricultural catchment reduced runoff in summer due to an increased infiltration, while they increased runoff in winter due to ground water exfiltration into the ditches (Moussa et al., 2002). Furthermore, the vegetation properties of linear structures changes seasonally. For example, grassed waterways reduce runoff less in winter due to a reduced hydraulic roughness of the dormant vegetation (Fiener and Auerswald, 2006).

In general, linear structures associated with patchiness can increase hydraulic connectivity if concentrated runoff is promoted, e.g. a ditch system following field borders can increase peak runoff rates up to 30% (Moussa et al., 2002). On the other hand, surface runoff can be slowed down and lowered if the linear structures increase the flow length of the runoff, as in constructed terrace systems (Lal, 1982; Mockus et al., 2002) or if runoff cross-section and hydraulic roughness are optimised to slow down runoff and facilitate infiltration, as in a long-term landscape experiment where peak runoff rate was reduced by 25% in the case of a flat-bottomed compared to a slightly incised grassed waterway cross-section (Fiener and Auerswald, 2005).

Tile drains, in general, also lead to a short cut, restricting the interaction between neighbouring patches and accelerating subsurface flow. Thus the temporal behaviour of the surface and the subsurface peak flow become more similar and lead to a faster and more pronounced reaction of the catchment (e.g. Klaus and Zehe, 2010). On the other hand, they may increase rain intake of the drained area, reducing direct runoff, and they reduce return flow downslope. The first of these will reduce sheet and rill erosion, while the second reduces ephemeral gullying. Hence the effect of tile drains on runoff behaviour of a catchment can vary in direction and may be relatively small compared to their effect on sediment loading (Savabi, 1993).

Despite the importance of stable linear structures shown in many small catchment studies, they have not been integrated into modelling studies intended to evaluate the overall effects of patchiness on surface runoff response. This is partly a result of a lack of detailed data on location and temporal behaviour, and partly because of the difficulties of adequately representing such small structures by commonly used fixed raster cell sizes (Anderton et al., 2002). The second problem at least might be partly solved using nested approaches to representing topography, where areas of concentrated flow are represented in higher spatial resolution (Heathwaite et al., 2005), or in triangulated irregular networks (TINs) that explicitly account for linear features in the landscape (Vivoni et al., 2005).

The effects of linear structures variable in time, like those associated with field management, are even more difficult to determine. Typical structures are plough furrows or back furrows along field border (Souchère et al., 1998; Takken et al., 2001a,b,c), and ephemeral gullies, which will be removed during subsequent tillage operations (Nearing et al., 1989; Morgan et al., 1998). However, in hydrological modelling the seasonal and/or event based change of runoff concentrating structures is commonly not accounted for, even though such changes might be a major source of model uncertainty. In general, the effect of complex linear structures associated with field layout, despite being shown in many experimental studies (e.g. Moussa et al., 2002; Fiener and Auerswald, 2005), seems to be underrepresented in most hydrological models.

5. Conclusions and summary

The review presented here addressed recent advances and challenges with respect to surface runoff generation in agricultural catchments and the effects of spatio-temporal patterns in land use and management. When considering temporal patterns of soil hydraulic properties at the scale of single fields the following statements can be derived from literature: (i) temporal patterns of soil bulk density related to tillage operation are very consistent and the derived equations can be used in pedotransfer functions to estimate vertical soil hydraulic properties, (ii) tillage-induced random and oriented roughness largely affect detention storage and runoff direction, (iii) hydraulic roughness increases with plant residue cover on the soil surface, (iv) soil cover either by living or dead plant material decreases soil crusting, and (v) soil crusts are removed by tillage operations. Other influences not reviewed here may include plant transpiration influences on soil moisture. In general, the most rapid changes between tillage operations occur for soil cover and random roughness, while aggregate stability and oriented roughness change much more slowly. The temporal variability of runoff generation potential in single fields decreases with decreasing management intensity and is the highest for CT systems and the lowest for NT systems.

This knowledge, derived from field and laboratory studies, has been incorporated in several, mostly hillslope or small catchment-scale, hydrological models. However, the simulation of the temporal dynamics of field-scale management effects on hydraulic behaviour remains challenging for some processes, e.g. the recovery of soil crust. There is a clear need to further develop and rigorously test these small-scale modelling tools, as they show great potential for studying the temporal effects of management on runoff generation in single fields.

The second part of this review addressed the combined spatio-temporal patterns of land use and management and their effect on surface runoff generation at the catchment scale. We specifically focussed on the roles of patchiness, the spatial organisation of patches and the effects of linear landscape structures associated with (field) patches. The concept of patchiness is not well established and tested in hydrological sciences, and studies on the effects of patchiness on surface runoff response of agricultural landscapes are relatively rare. Nevertheless, several studies indirectly address this topic, indicating that increasing patchiness due to decreasing field sizes reduces surface runoff, especially in the case of Hortonian runoff. The effect of patchiness on runoff generation is small during winter, when the hydraulic properties of fields are very similar. In contrast, during summer, patchiness becomes an important parameter for surface runoff generation, as large spatial variability in hydraulic properties exists. The effects of patchiness increase with management intensity because of the increasing temporal variability of runoff generation potential within single fields. The influence of linear structures, which can either promote or dampen runoff response, is less frequently considered in field studies and scarcely incorporated in models.

It can be concluded that increasing patchiness and its associated structures substantially affect (mostly reduce) the surface runoff generation potential of agricultural catchments. Conversely, however, some linear structures (e.g. ditches along field borders) may also increase runoff to streams by increasing connectivity of high-flow paths. Differences in runoff behaviour in different agricultural regions can be expected due to the large regional differences in field sizes. However, field sizes are commonly not part of official statistics and large-scale studies are missing that determine field sizes from other data sources, e.g. remote sensing. Nevertheless, an indication for field size for the European Union could be derived from statistics of the median size of agricultural holdings (Fig. 12).

Clearly, the largest gaps in surface runoff (and erosion) research are related to the effects of temporal dynamics of patch interactions, the influence of the spatial organisation of patches, and the interaction with linear structures that often dominate hydraulic connectivity on the catchment scale. While large changes in the structure of agricultural landscapes occur throughout the world, our knowledge of the consequences and the availability of (modelling) tools to predict the effects is still limited.

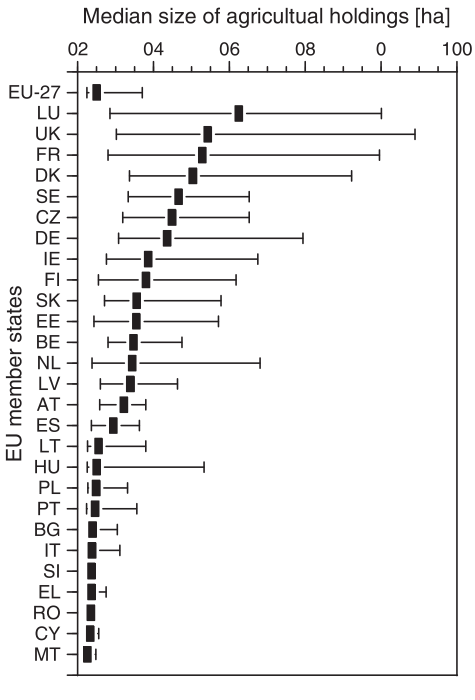

Fig. 12. Median size with the 25% and 75% percentiles (bars) of agricultural holdings in 2005 within the EU (EUROSTAT Pocketbooks – Agricultural Statistics – Main Results 2006–2007). The median and the 25% and 75% percentiles were calculated from the five categories given in statistics by linear interpolation within each category; abbreviations of EU member states follows ISO 3166 code list (ISO, 2009).

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Appendix A. Concept and terminology of semivariances

Measurements reflect small segments in time and space. The squared difference between two measurements $(x_i - x_{i+1})^2$ usually increases with the distance (lag) between both. To quantify this general behaviour for a certain property, half of these squared differences are averaged for different lag classes and plotted against the average lag within a class. This leads to the so-called experimental semivariogram (Fig. A1, top). The experimental semivariogram still has some scatter due to the limited number of measurements and gaps between the lag classes. The general behaviour can then be estimated by fitting functions to the experimental semivariogram, which leads to the so-called theoretical semivariogram or semivariogram model (Fig. 1A, top).

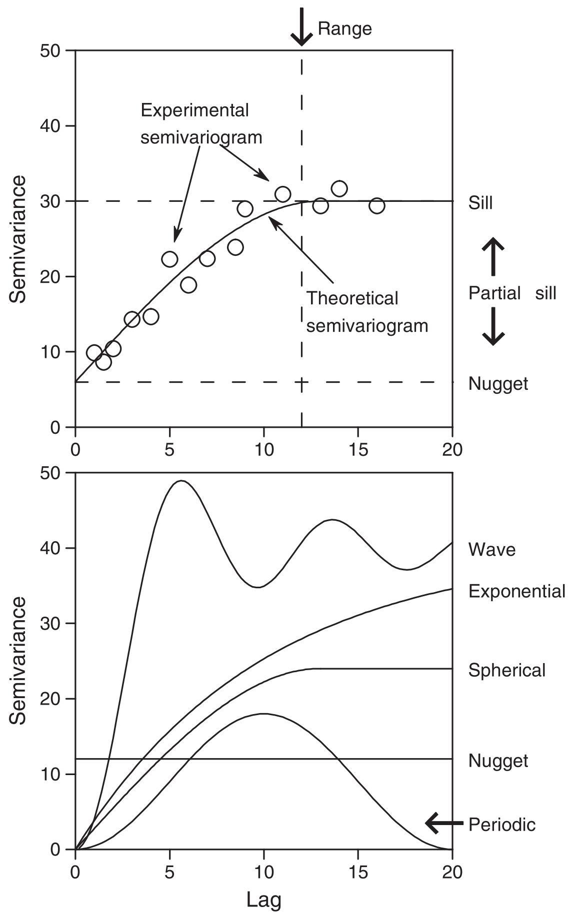

Fig. A1. Example of an experimental semivariogram and different types of theoretical models (wave, exponential, spherical, nugget and periodic) that can be described by three parameters (the range, the partial sill and the nugget; the partial sill and the nugget yield the total sill).

Several functions are frequently used to describe this variation like the nugget, the spherical, the exponential, the periodic and the wave functions (Fig. 1A, bottom). Each of these functions can be interpreted in view of the property and can often be associated with a process causing the variability of this property. The nugget function reflects the noise in the data, which may go back to measurement errors. Most often spherical models are found, which evolve when a pattern exists and the full variability of this pattern is found at shorter distances than the maximum distance covered by the measurements. This distance, after which full variability or loss of autocorrelation can be expected, is called range. At lags beyond the range, the semivariance remains constant and forms the so-called sill. A missing sill, like in the exponential model, indicates that the variability would have been larger if the study area had been somewhat larger. Regular patterns, like seasonal variation, usually lead to periodic or wave functions. The wave function fades out at larger distances due to slight deviations in the regular pattern, while the pattern is still precise even at large lags with the periodic function.

Patterns in space or time are often caused by several processes simultaneously, such as the variation of soil caused by geology and land use. This then leads to nested semivariograms. Usually, at least two functions are nested, one quantifying the noise (nugget) and one for the pattern. Each function of a nested semivariogram has a partial sill, which together yield the total sill of the property (Fig. A1, top).

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